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EXTREMES OF LOW ATMOSPHERIC DENSITY NEAR THE GROUND FOR ELEVATIONS UP TO 15,000 FEET FOR MIL-STD-210B

Rene V. Cormier

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

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RENÉ V. CORMIER

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13. ABSTRACT

Atmospheric density, especially low values thereof, is important to aircraft takeoff and landing operations. Such extremes must be considered in aircraft design and are therefore to be included in MIL-STD-210B. This document provides environmental design criteria to designers of military equipment, and requires for the most extreme area and month, values of low density that are equalled or surpassed during, 1, 5, 10, and 20 percent of the time for ground elevations up to 15,000 feet. Typical temperatures accompanying these values, needed for engine power calculations, are also required. This report provides these densities and temperatures. In addition, empirical equations, being used by the USAF Environmental Technical Applications Center, for estimating extremes of low density near the ground, are evaluated.

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1. INTRODUCTION

Air density greatly affects aircraft aerodynamic and engine performance[1]. The density of the air near the ground is especially important in aircraft design since the lower the density, the longer the takeoff roll required by fixed-wing aircraft and the less weight a rotary-wing aircraft can lift. Concurrent temperature also has an important secondary effect and is necessary for a thorough analysis of engine performance (Crotty, 1969). Consequently, the USAF Aeronautical Systems Division[1] has requested that extremes of low density with concurrent temperature near the ground be included in the forthcoming MIL-STD-210B, "Climatic Extremes for Military Equipment." This document provides environmental design criteria for military equipment intended for worldwide use. Since air density decreases with height, extremes are needed for ground elevations up to the highest elevations contemplated for military operations.

MIL-STD-210A, the current standard, includes density extremes for different altitudes, but these are "free-air" values and do not represent the much lower densities which can occur near the ground at corresponding elevations. Nonetheless, designers have wrongly used MIL-STD-210A values or the U.S. Standard Atmosphere (COESA, 1962) and problems have resulted[1,2].

1. Hq ASD/WE (Mr. R.E. Dean) Wright-Patterson AFB, OH, letter of 23 Nov 1971, Subject: MIL-STD-210B, to AFCRL/LKI (Mr. Sissenwine), L.G. Hanscom Field, Mass.

2. Hq ASD/ENFD (Mr. R. H. Klepinger) Wright-Patterson AFB, OH, letter of 14 April 1972, Subject: Revision of MIL-STD-210A, to ASD/WE (Capt McKechney) Wright-Patterson AFB, OH.

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Another problem related to establishing specific design criteria has been the absence of USAF staff guidance on the highest ground elevations at which various types of aircraft possessing "worldwide" capability must operate. Values of elevations used for design have varied greatly[1] and aircraft have been often called upon to operate in climatic areas under conditions at or beyond their density design limits[2]. Prerequisite air staff guidance on the family of elevations for operatio · ~f the several types of aircraft has been requested[3] but no authoritative source of such information has yet responded.

This report provides values of low density (with concurrent temperature) from the most extreme month in the most extreme area, that are equalled or surpassed during 1, 5, 10, and 20 percent of the time for ground elevations to 15,000 feet. This, the highest elevation being contemplated for operation by the U.S. Army (Sissenwine and Gringorten, 1969), should also be reasonably close to the highest elevations, contemplated for takeoff and landing of any Air Force aircraft but probably far higher than applicable to massive bombers and transports.

Density is not measured per se but can be calculated from coincident observations of temperature, relative humidity, and pressure. Since such coincident observations are not available for many stations, the practice[4] of the USAF Environmental Technical Applications Center (ETAC) has been to estimate the surface-level density extremes from empirical equations developed by Kochanski (1961). These require the monthly mean of daily maximum and minimum temperatures, relative humidity, and pressure. This approach was not used in this study for two reasons. One, MIL-STD-210B requires the 1 percent density extreme and the empirical equations provide only the 5, 10, and 20 percent extremes. Two, the equations were developed with data from 15 stations and tested against data from 15 other stations; of these stations, only 3 were from areas having extremely low densities and only one had an elevation above 4000 feet. Therefore, although the equations were shown to provide excellent results for both the development and test samples, their utility for estimating density extremes for areas of the world noted for low density and for elevations up to 15,000 feet was not known.

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1. loc. cit., footnote 1, page 1.

2. loc. cit., footnote 2, page 1.

3. AFCRL/LKI (Mr. N. Sissenwine) L.G. Hanscom Field, Mass, letter of 19 Jan 1972, Subject: MIL-STD-210B and Density Altitude Extremes for Aircraft Take-Off and Landing, to USAF/AFRDD (Lt. Col Tilman), Washington, D.C.

4. USAF ETAC/EN (Lt Col J.H. Windt), Washington, D.C., letter of 16 Dec 1971, Subject: MIL-STD-210 Density Altitude, to AFCRL/LKI (Mr. N. Sissenwine), L.G. Hanscom Field, Mass.

Consequently, this study used actual density distributions to determine the 1, 5, 10, and 20 percent extremes. The utility of the empirical equations for estimating density extremes for these same stations was then also determined.

2. DATA

Choosing the areas of the world and month with lowest density for elevations to 15,000 feet is not straightforward as surface densities are not routinely calculated and published. However, an examination of the perfect gas law ($\rho = P/RT^*$, where ρ is density, P is pressure, R is the gas constant, and T* is virtual temperature) and knowledge of the magnitudes and the possible percent variation of the variables which determine density, lead to the following reasonable assumption: Density extremes for a given elevation will occur at stations having extremes of high temperature; low pressure and high humidity being much less important.

Using this assumption, 48 stations representing different hot regions of the world and elevations from 10 to 14,753 feet were selected for study from climatological tables published by the British Meteorological Office (1958) and the World-Wide Airfield Summaries (1967-1971). For each station, the month having the highest mean daily maximum temperature was selected (when 2 months had nearly equal temperatures, both were selected). Stations and months selected are given in Table 1. Stations below approximately 5500 feet are generally found in North Africa and the Middle East -- above this elevation, in the United States and South America.

Table 1. Stations Selected and Data Used to Determine Worldwide Low-Density Extremes for Ground Elevations to 15,000 Feet. The pressure column indicates the source used to calculate coincident hourly station pressures when these were not directly available. Data from stations marked with an asterisk were rejected in the final analysis

Elevation (ft)	Station	Month(s)	Period of Record	No. Of Observations	Pressure
10	Abadan, Iran	Jul, Aug	49-55, 57-58, 63-68	3652; 3667	Sea Level pres.
112	Baghdad, Iraq	Jul	49-55, 63-68	1778	Sea Level pres.
184	Kuwait, Arabia	Aug	63-68	983	Sea Level pres.
318	Allahabad, India	May	54-63	904	Sea Level pres.
492	Quargia, Algeria	Jul	57-67	1116	Sea Level pres.

Table 1. Stations Selected and Data Used to Determine Worldwide Low-Density Extremes for Ground Elevations to 15,000 Feet. The pressure column indicates the source used to calculate coincident hourly station pressures when these were not directly available. Data from stations marked with an asterisk were rejected in the final analysis (Cont)

Elevation (ft)	Station	Month(s)	Period of Record	No. of Observations	Pressure
656	Aswan, Egypt	Jun, Jul	57-66	1534; 1613	Sea Level Pres.
663	Kanaquin, Iraq	Aug	49-55	310	Sea Level Pres.
817	Karima, Sudan	Jun	55-63	831	Sea Level Pres.
860	*Adrar, Algeria	Jul	59, 61 64-67	175	Sea Level Pres.
1079	Bamako, Mali	Jun	57-67	1565	Sea Level Pres.
1883	El Obeid, Sudan	Apr	56, 58-63	778	Sea Level Pres.
1900	Fes-Sais, Morocco	Jul	61-62, 65-67	478	Sea Level Pres.
2047	*Riyadh, Saudi Arabia	Aug	58-68	1317	Available & Sea Level Pres.
2661	*Bechar, Algeria	Jun	57-62, 65-67	1092	850 mb height
3314	*Kandahar, Afghanistan	Jul	66-68	150	850 mb height
3520	*Ain-Sefra, Algeria	Jul	57-61	261	850 mb height
3736	*Quarzazate, Morocco	Jul	57-67	592	850 mb height
3773	Torreon, Mexico	Jun	49-60	2510	Sea Level Pres.
3950	Tehran, Iran	Jun	49-53, 57-58, 63-68	945	Sea Level Pres.
4331	Kermanshah, Iran	Jul	57-58, 63-68	885	Sea Level Pres.
4521	Zahedan, Iran	Jul	57-58, 63-68	882	Sea Level Pres.
4685	Chihuahua, Mexico	Jul	53-69	1713	Sea Level Pres.
4856	Drosh, Pakistan	Jul	54-63	856	Sea Level Pres. & 850 mb height

Table 1. Stations Selected and Data Used to Determine Worldwide Low-Density Extremes for Ground Elevations to 15,000 Feet. The pressure column indicates the source used to calculate coincident hourly station pressures when these were not directly available. Data from stations marked with an asterisk were rejected in the final analysis (Cont)

Elevation (ft)	Station	Month(s)	Period of Record	No. of Observations	Pressure
4938	Shiraz, Iran	July	57-58, 63-68	748	Sea Level Pres.
5200	Sprinagar, Kashmir	Jul	56-63	435	850 mb height
5240	Esfahan, Iran	Jul	49-51, 57-58, 63-68	2240	Sea Level Pres.
5459	Ifrane, Morocco	Jul	61-62, 64-65, 67	318	850 mb height
5735	Kerman, Iran	Jul	57-58, 63-68	564	Sea Level Pres.
5761	Trinidad, Colo, USA	Jul	48-58, 61	8906	Available
5869	Kabul, Afghanistan	Jul	57-58, 66-68	262	850 mb height
6172	Colorado Sprgs, Colo, USA	Jul	48-71	14, 376	Available
6352	Raton, N. Mex, USA	Jul	49-52, 56-61	4857	Available
6719	Elduret Kenya	Mar	57-61	1014	850 mb height
7016	Fort Bridger, Wyo, USA	Jul	48-54	5183	Available
7535	Alamosa, N. Mex, USA	Jul	48, 56-51	5004	Available
7586	Bryce Canyon, UT, USA	July	49-64	11, 901	Available
7628	Asmara, Ethiopia	Apr	57-59	185	Available
8291	*Cuenca, Ecuador	Sept	45-47, 68	187	Available
8432	Cochabamba, Bolivia	Oct	42-49	639	Available
9226	Quito, Ecuador	Aug, Oct	57, 59-68	697; 778	Available & Sea Level Pres.
9350	Sucre, Bolivia	Nov	44-48	247	Available
9731	Ipales, Colombia	Sept	68-70	254	Available

Table 1. Stations Selected and Data Used to Determine Worldwide Low-Density Extremes for Ground Elevations to 15,000 Feet. The pressure column indicates the source used to calculate coincident hourly station pressures when these were not directly available. Data from stations marked with an asterisk were rejected in the final analysis (Cont)

Elevation (ft)	Station	Month(s)	Period of Record	No. of Observations	Pressure
11,348	LaQuiaca, Argentina	Nov.	57-58, 65-68	313	Available
11,529	*Leh, Kashmir	Jul	56-63	237	700 mb height
11,798	*Lhasa, Tibet	Jun	57-64	903	Available
12,546	Juliaca, Peru	Nov.	64-69	702	Available
13,350	La Paz, Bolivia	Nov.	42-48 58-61	597	Available
14,753	Cerro, Peru	Nov.	57-58 61-66	492	Available

For a given station/month, the Data Processing Division of ETAC (Asheville, NC) computed densities from coincident observations of station temperature, pressure, and humidity for each hourly observation available within the period of record noted in Table 1. Coincident station pressure when not available was computed from either sea-level pressures, 850-mb heights, or 700-mb heights as indicated in Table 1. Those computed densities were then ranked, and the low densities equalled or surpassed in 1, 5, 10, and 20 percentiles of the observations for a particular station/month determined. The mean temperature of the observations associated with each of these percentiles at each station was then computed. For example, if the 1 percentile density at a particular location is equal to A, and five observations had density values equal to A, then the associated mean temperature value would be the mean temperature of the five observations with a density value of A.

3. PROCEDURE

The 1, 5, 10, and 20 percentile densities for each station/month and associated mean temperatures were plotted as a function of station elevation and examined for internal consistency. This examination indicated that densities from nine stations appeared to be grossly too low. Before rejecting these outright, the 5, 10, and 20 percentile densities were compared with estimates of these same percentile computed using the empirical estimating equations[1]. These comparisons confirmed the original appraisal, and the stations were excluded from further analysis (these nine stations are marked with an asterisk in Table 1). Six of the nine indicate an average of less than two observations per day; this would account for the bias toward lower than reasonable densities if the one observation were taken near midday. No reasons for the low densities are apparent at the three remaining stations; perhaps computational and/or coding errors were involved.

Rather than plot density versus elevation to determine the worldwide envelope for the 1, 5, 10, and 20 percentile density extremes for the remaining 39 stations, the percentile densities at each station were converted to and plotted in terms of percent departure from the standard density (COESA, 1962) for the altitude corresponding to the station elevation. This was done because the magnitude of the normal decrease of density with altitude tends to mask the variation of density extremes with height. Standard densities to 15,000 feet are given in Table 2.

Table 2. Standard (1962) Densities for Altitudes to 15,000 Feet

Altitude	Density	
	(kg/m^3)	(lb/ft^3)
0	1.2250×10^0	7.6474×10^{-2}
1000	1.1895	7.4621
2000	1.1549	7.2098
3000	1.1210	6.9983
4000	1.0879	6.7916
5000	1.0556	6.5896
6000	1.0239	6.3922
7000	9.9303×10^{-1}	6.1993
8000	9.6287	6.0010
9000	9.3341	5.8271
10,000	9.0464	5.6475
11,000	8.7655	5.4721
12,000	8.4914	5.3010
13,000	8.2239	5.1340
14,000	7.9628	4.9710
15,000	7.7081	4.8120

1. Section 5 shows that the use of these equations to estimate worldwide density extremes for elevations to 15,000 feet results in rms errors significantly greater than found by Kochanski (1961). However, these errors are still much smaller than the apparent errors in the data from the nine stations.

4. RESULTS

Figure 1 contains a plot of the 1 percentile densities for the 39 stations. Also included on Figure 1 is a quasi-envelope for these values with two points falling outside of the envelope. However, the envelope was drawn within the purpose and philosophy of MIL-STD-210B of finding worldwide extremes that are generally "representative" of an/area or condition rather than anamolies. The envelope as drawn fulfills that function and is recommended.

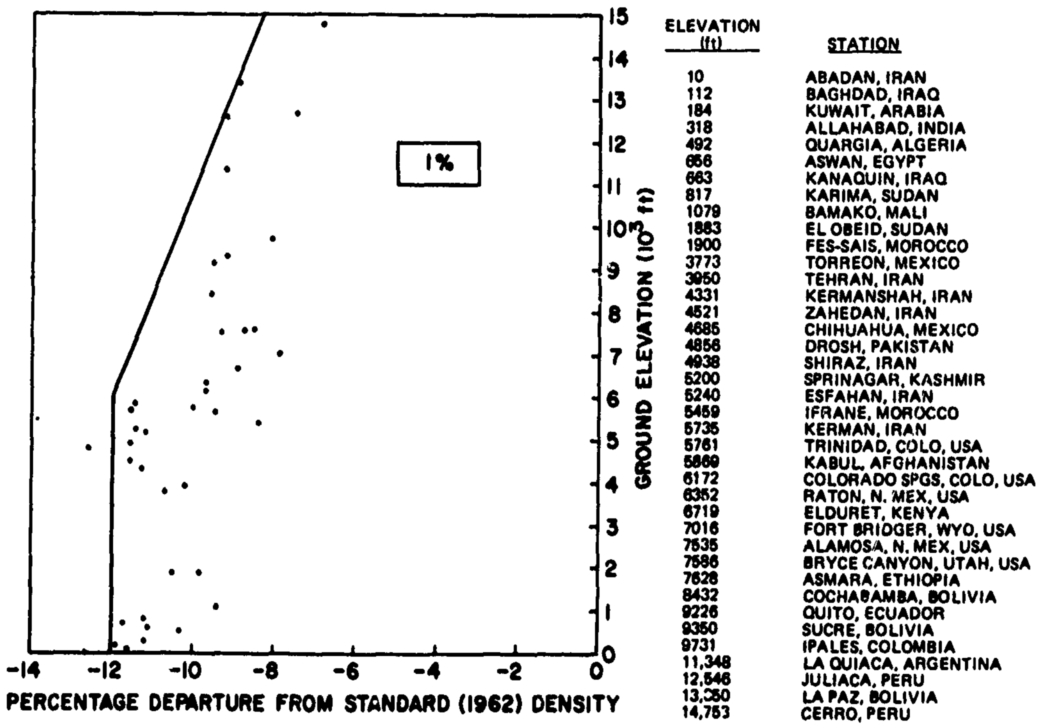

Figure 1. One Percentile Densities (Extreme Month) for Listed Stations (to ~ 15,000 Feet) and the Envelope of These Densities

It is recognized that other locations and/or months might be uncovered that could conceivably alter the envelope, but such a change would be small since the sample of data used is quite representative of the near-ground, extreme low densities over the world. The envelope was not drawn independently of the other percentiles. Similar point plots for the 5, 10, and 20 percentiles were constructed and examined collectively, and then the envelopes were drawn. The recommended percentile curve shows a density that is 12 percent below standard from sea level to 6000 feet. This negative departure then decreases linearly with ground elevations approximately 0.4 percent per 1000 feet up to 15,000 feet.

It is of interest to compare this 1 percent envelope of near-ground densities for elevations to 15,000 feet with the envelope of "free-air" densities for comparable altitudes (1 km and above) being recommended for MIL-STD-210B (Richard and Snelling, 1971). Figure 2 shows that near-ground density departures are much more extreme than free-air densities. This elucidates the problems mentioned in Section 1, that of assuming free-air densities as representative of surface densities in design. Two other points are worth noting: (1) the slope in percent departure from standard above 6000 feet for the 1 percentile near-ground curve is comparable but somewhat less than in the free-air case, and (2) the free-air density departure from standard below 6000 feet appear to be not extreme enough when compared to near-ground departures. The point at 1 km (3280 feet) which governs the shape of the free-air envelope below 6000 feet, represents the 1 percentile density over north-central United States. Free-air densities at altitudes below 6000 feet over regions where near-ground density extremes occur – northern Africa and the Middle East – might conceivably show greater departures than indicated on Figure 2, but radiosonde data are not available to show this.

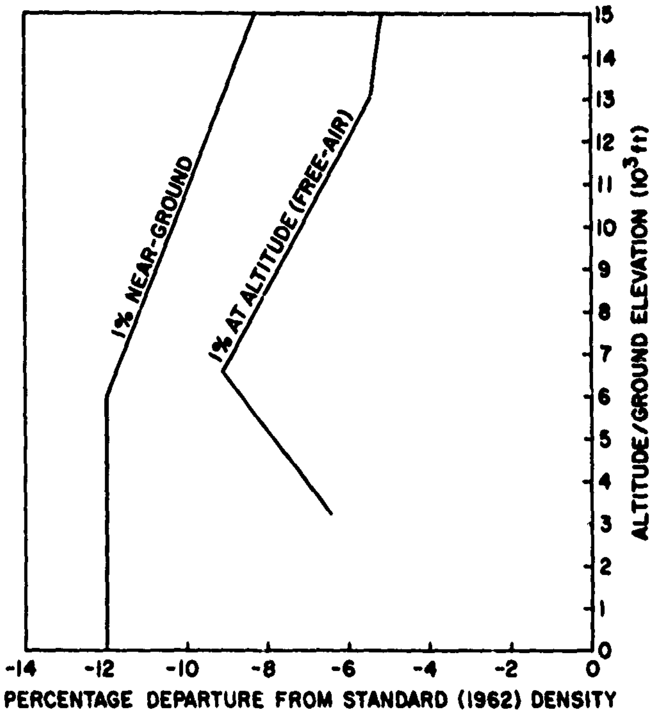

Figure 2. Envelope of 1 Percentile Densities for Ground Elevations to 15,000 Feet Compared to Envelope of 1 Percentile "Free-Air" Densities for Corresponding Altitudes

Figure 3 is a composite figure presenting the 1, 5, 10, and 20 percentile worldwide "worst" area and month, low density extremes for elevations to 15,000 feet for MIL-STD-210B. The 5, 10, and 20 percentile envelopes have shapes similar to the 1 percentile envelope. The 5 percentile curve shows a constant −11.5 percent departure from standard density up to 6000 feet, the 10 percentile curve a constant −11.0 percent, and the 20 percentile curve a constant −10.5 percent.

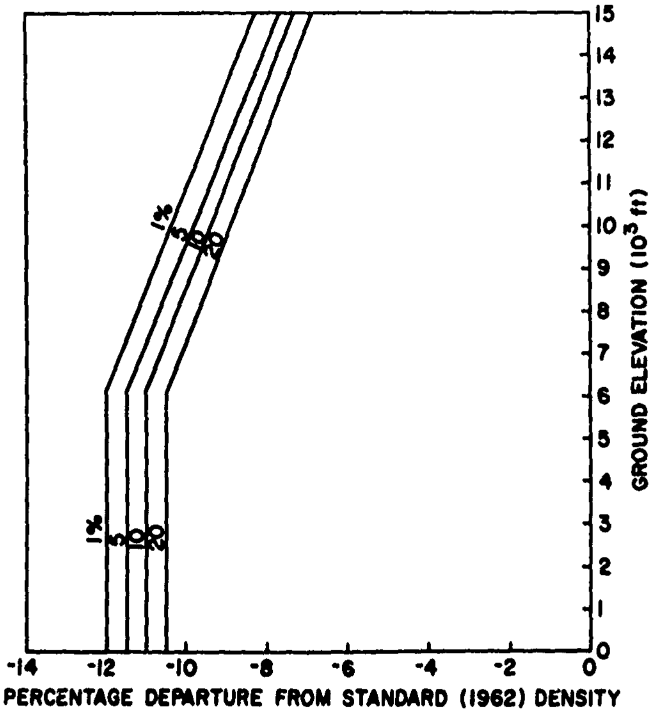

Figure 3. Low Density Extremes - 1, 5, 10, and 20 Percentiles - for Ground Elevations to 15,000 Feet for MIL-STD-210B

Figure 4 is the companion plot for the mean temperatures associated with the 1, 5, 10, and 20 percentiles of density. These curves show a smaller lapse rate of temperature in the lower layers and a lapse rate which approaches 4°F per 1000 feet at higher elevations.

Williams (1972) in investigating worldwide, high temperature extremes versus ground elevations for MIL-STD-210B, also presented curves of temperatures versus elevations. The data cover elevations up to 9000 feet and are representative of the hot locations in the southwest United States. His curves present 1, 5, and 10 percentile high-temperature extremes rather than the mean temperatures associated with the 1, 5, and 10 percentile densities shown in Figure 4. They show shapes similar to the curves in Figure 4, except that the lapse rates aloft are steeper and approach the dry adiabatic (5.4°F per 1000 feet). Williams concludes and recommends that this lapse rate should be used universally to determine worldwide temperatures at higher elevations. Although not directly comparable, the curves in Figure 4 do not support his conclusion. If constructed, the lapse rate of the 1, 5, and 10 percentile temperatures from the locations used in this study would probably show an even further departure from the adiabatic than the lapse rate of 4°F per 1000 feet associated with the 1, 5, and 10 percentile densities of Figure 4.

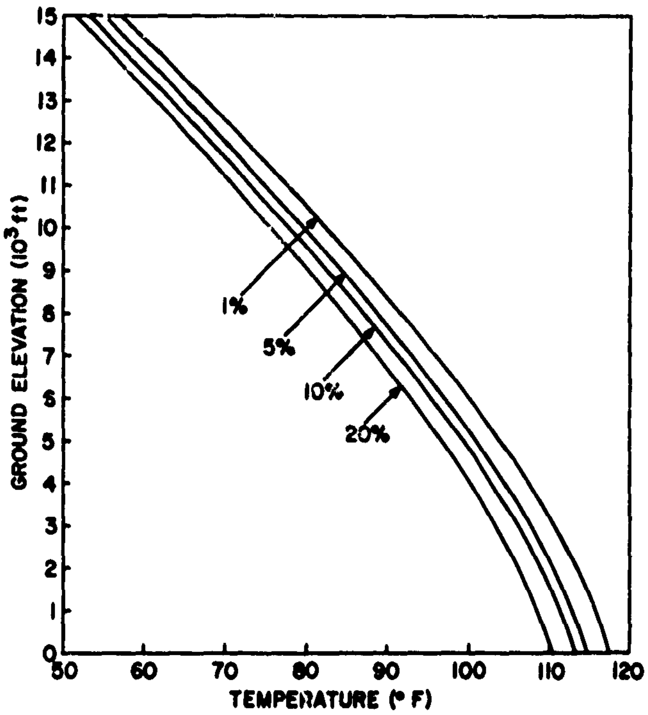

Figure 4. Mean Temperatures Associated With the 1, 5, 10, and 20 Percentiles of Density for Ground Elevations to 15,000 Feet

5. EMPIRICAL EQUATION EVALUATION

Empirical equations for estimating the 5, 10, and 20th percentiles of air density at station level were developed and tested by Kochanski (1961) and have been used in place of actual density distribution. As a by-product of this study, the equations were further evaluated since the necessary data were on hand for 21 of the 39 stations used in the basic study. Table 3 provides the results of this evaluation. Presented are the rms and extreme errors found by Kochanski in his evaluation, using independent data from 15 stations, and those found for the 21 stations used in this study. Looking at the 5 percentile values, this study shows rms errors over six times greater than those found by Kochanski; although it must be emphasized that the units of error are grams per cubic meter. The rms error when expressed as a percent of the magnitude of near sea-level density is thus only an error of about 2 percent.

Table 3. A Comparison of Root Mean Square and Extreme Errors (gm/m^3) Obtained by Using the Empirical Equations to Determine Low Density Extremes in This and Kochanski's (1961) Study. The number of cases is in parentheses

	5 Percentile		10 Percentile		20 Percentile	
	RMS Errors	Extreme Errors	RMS Errors	Extreme Errors	RMS Errors	Extreme Errors
Kochanski's Study (15)	3.0	10.6	2.4	8.8	1.8	6.0
This Study, All Stations (21)[1]	18.7	32.0	17.1	28.0	16.3	34.0
This Study, Stations ≥ 5000 ft (10)	23.4	32.0	21.5	28.0	20.4	34.0
This Study, Stations < 5000 ft (11)	13.0	27.0	11.6	25.0	11.3	26.0
This Study, Stations < 1100 ft (7)	7.8	16.0	7.1	14.0	5.9	10.0

1. The number of cases in All Stations (21) is less then the 39 used in Section 3 because the data needed to use the empirical equations were readily available for only 21 of the 39 stations.

To investigate the contribution of elevation to the rms error, the 21 stations were divided between those above and those below 5000 feet, and then the rms and extreme errors were computed for this stratification. These results are also given in Table 3, and they indicate that the use of the equations would result in rms errors nearly twice as great above 5000 than below 5000 feet. This is especially significant since the percent error would be much greater above 5000 feet because of the normal decrease of density with increasing altitude. This corroborates initial doubts as to the applicability of the equations to estimate density extremes at elevations significantly higher than stations used in the equation developmental sample.

As a further check into the effect of altitude on the accuracy of the estimating equations, rms and extreme errors were computed for only stations with elevations under 1100 feet. This elevation limit was chosen because all of the stations in Kochanski's independent test sample were below 1100 feet. These results, also given in Table 3, now indicate rms errors about 2-1/2 times greater than

Kochanski's errors. However, these stations were chosen on the basis of having extremely low densities whereas Kochanski's stations were not.

Had the empirical equations been used to estimate the envelope of 5 percentile density extremes for ground elevations to 15,000 feet, the curve labelled "5% From Empirical Equations" in Figure 5 would have been obtained. Also on Figure 5 is the 5 percentile envelope from the density distributions themselves. The empirical equations increasingly overestimate the percent departures from standard density from the surface to 15,000 feet.

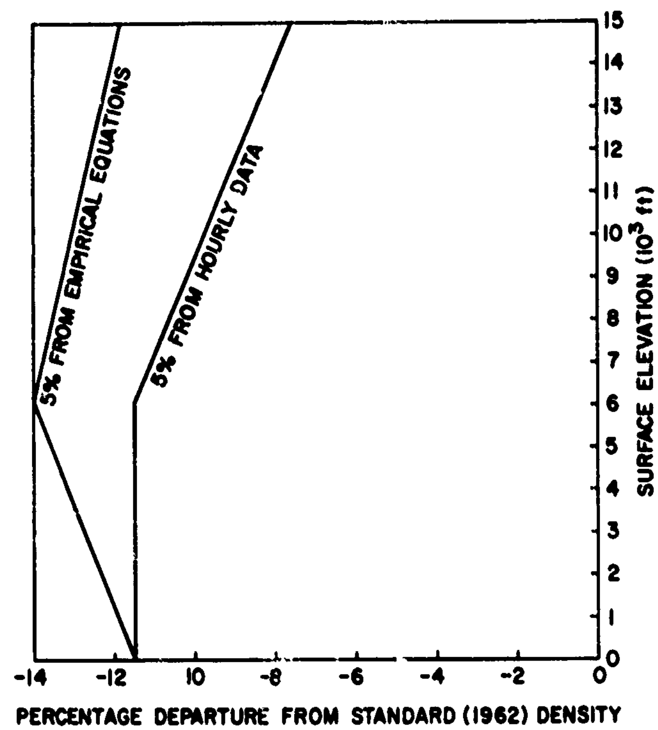

Figure 5. Envelope of 5 Percentile Densities Determined from Hourly Observations Compared to Envelope Determined from Empirical Equations (Kochanski, 1961) for Ground Elevations to 15,000 Feet

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